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Final Report

SWIMMING BEHAVIOR OF INDIVIDUAL ZOOPLANKTERS DURING NIGHT-TIME FORAGING

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Amatzia Genin, Jules Jaffe, Duncan McGehee developed a method for automatically tracking individual plankters swimming through the imaging volume, and applied the method to track approximately 280,000 animals. Net samples indicated that most of the acoustic targets tracked were euphausiids in the 11-13 mm range. This was supported by target strength measurements coupled with an acoustic scattering model for euphausiids based on the distorted-wave Born approximation. Total movement of the animals was treated as the sum of two components: (1) an average component shared by all the animals, due in the horizontal dimension to currents and in the vertical dimension to internal waves, and (2) a "random" component due to the behavior of the individual animals. The average horizontal speeds measured acoustically agreed with measurements from a current meter mounted on the mooring. the random component of euphausiid movement was isotropic in three dimensions with the distribution of velocities in each dimension approximated by a zero-mean Gaussian random variable whose standard deviation depended on the time of night. One data set was dominated by small fish. Here the random behavior was not Gaussian, and was probably affected by the presence of the sensor. A Monte Carlo simulation of euphausiid behavior was made by applying velocities from a zero-mean Gaussian distribution to thousands of individuals, and filtering the modeled movement through a mathematical model of fish TV. This yielded a set of model-based observations that agreed with the *in situ* measurements.

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Executive Summary

Amatzia Genin and Jules Jaffe deployed the three-dimensional acoustical imaging system FishTV in a moored configuration for three nights at 26 m depth in the Gulf of Eilat in June, 1994. The system collected several hours of acoustical images of zooplankton and small fish. Duncan McGehee joined Genin and Jaffe in proposing to the Office of Naval Research (ONR) that these data be analyzed in such a way as to extract the swimming behavior of the organisms during night-time foraging. ONR agreed, and a grant was made to the Woods Hole Oceanographic Institution (WHOI). Later McGehee moved to Tracor Aerospace, and a subcontract agreement was made between WHOI and Tracor for McGehee to complete the work there. This Final Report is submitted in fulfillment of that subcontract.

Genin, Jaffe, and McGehee developed a method for automatically tracking individual plankters swimming through the imaging volume, and applied the method to track approximately 280,000 animals. Net samples indicated that most of the acoustic targets tracked were euphausiids in the 11-13 mm range. This was supported by target strength measurements coupled with an acoustic scattering model for euphausiids based on the distorted-wave Born approximation. Total movement of the animals was treated as the sum of two components: (1) an average component shared by all the animals, due in the horizontal dimension to currents and in the vertical dimension to internal waves, and (2) a "random" component due to the behavior of the individual animals. The average horizontal speeds measured acoustically agreed with measurements from a current meter mounted on the mooring. The random component of euphausiid movement was isotropic in three dimensions with the distribution of velocities in each dimension approximated by a zero-mean Gaussian random variable whose standard deviation depended on the time of night. One data set was dominated by small fish. Here the random behavior was not Gaussian, and was probably affected by the presence of the sensor. A Monte Carlo simulation of euphausiid behavior was made by applying velocities from a zero-mean Gaussian distribution to thousands of individuals, and filtering the modeled movement through a mathematical model of FishTV. This yielded a set of model-based observations that agreed with the *in situ* measurements.

A manuscript is currently in preparation for a 1999 submission to *Limnology and Oceanography*.

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Long-Term Goals and Immediate Objectives

The long-term goal of this research is to learn in what ways and to what extent the individual behavior of zooplankters can affect overall zooplankton population distributions.

The immediate objectives of this research project were two-fold: 1) to learn about euphausiid foraging strategies by observing the swimming behavior of large numbers of undisturbed individuals in the photic zone at different times of night, and 2) to learn how euphausiids partition energy between the vertical and horizontal components of motion at different times of night, particularly during vertical migration.

Approach

McGehee and Jaffe (1996) measured the three-dimensional tracks of over 300 individual plankters from a one-minute-long sequence of 3-D images collected with the three-dimensional acoustical imaging system FishTV (FTV) off the coast of California in March, 1993. The data were exciting because they showed evidence of swimming behavior related to area-restricted searching, an optimum foraging behavior for animals in a patchy food environment. However, the tracks were measured by hand, a laborious task indeed. In July 1994 Genin and Jaffe collected a much larger FTV data set in the Red Sea. Part of the data were collected during a three night moored deployment of the instrument at a depth of 27 m in the Gulf of Eilat, approximately 1.2 km from shore, in water 280 m deep. The transducer had a large vane attached, intended to keep it aimed up-current, so that ensonified animals would be undisturbed by the hardware. The volume of water ensonified was approximately 5 m^3. The measurements were supplemented by simultaneous flow measurements using an S4 current meter. Two BONGO net tows made during the experiment indicated that euphausiids (*Euphausia diamedae*, *E. sanzoi*, *Stylocheiron abbreviatum*, and *S. affine*) were well represented in the fauna (10's to 100's per m^3).

The research performed under the present contract examined data from the moored deployment. The overall approach was to develop a method for automatically tracking the animals in this data set and to examine the swimming trajectories thus determined at various times of night, with the goal of learning more about zooplankton night-time foraging, vertical migration behavior, and the partitioning of energy between horizontal and vertical components at different times of night.

Work Completed

In FY96 a robust algorithm was developed for tracking acoustic targets in the FTV 3-D image sequences. In FY97 we used these methods to track approximately 280,000 individual zooplankters and fish. FY98 was devoted to analysis of the target tracks. The analysis was limited to the nights of

27-28 June, and 28-29 June, 1994, with particular emphasis on the first of these two nights, when 8-minute-long image sequences were collected approximately every 30 minutes.

Results

As might be expected, the number of acoustic targets observed increased dramatically after sundown, and decreased again after first light in the morning. The acoustic target strengths were measured, and the maximum target strength for each target was determined. This may be used as a very approximate measure of the length of the animal, provided it is a euphausiid, using a distorted wave Born approximation (DWBA) scattering model (Stanton et al, 1998; McGehee et al, 1998a). Before sundown, the peak in the acoustic target strength distribution was about -88 dB, corresponding at 445 kHz to euphausiids approximately 7 mm in length. This peak was almost certainly an artifact of the tracking algorithm, which did not report targets below -90 dB. The true peak was probably at a much lower target strength. Once it was completely dark, however, the peak shifted to about -75 dB, corresponding to euphausiids about 12 mm in length. This agrees with measurements from the BONGO net samples. In one of the image sequences the whole target strength picture changed, with the peak in the distribution at approximately -50 dB. These animals were clearly fish, for which we do not have good scattering models at 445 kHz.

The motion of the targets was separated into two parts: a mean component, ascribed to bulk water movement (or possibly vertical migration, in the vertical dimension); and a random component, ascribed to random animal behavior superimposed upon the bulk motion. The mean horizontal component of tracks of the smaller targets (TS < -75 dB) was highly correlated with the horizontal flow measured simultaneously by an S4 current meter. These targets also exhibited strong mean vertical motions throughout the night, both up and down, apparently due to internal waves. Because of the strength of the mean vertical water motion, direct measurements of daily vertical migration rates were not possible.

We also discovered in many of the data a 2-second period vertical oscillation that we ascribe to sensor motion. This oscillation limited our ability to examine the vertical component of random behavior in those data. However, in the data where this vertical oscillation was not present, we have been able to compare the vertical component of the random energy with the random energy devoted to horizontal swimming. Previously (before we discovered the vertical oscillations in the data) we had publicly declared that the animals put substantially more energy into the vertical component of swimming than into the horizontal component, possibly for "hop-and-sink" foraging. We now know that was an artifact of the vertical oscillations in the sensor. It appears now that the random component of zooplankton swimming behavior is isotropic in three dimensions.

Using the mean random speeds, we estimate that the -75 dB targets (euphausiids) swam slower than 2 cm/s on average, whereas the fish swam at about 4 cm/s on average.

In recent years the use and popularity of Individual Based Models (IBMs) in behavioral ecology has grown with the widespread availability of high speed personal computers (e.g., DeAngelis, 1992). These models provide a set of behavioral rules to large collections of computer "animals," turn them loose to move and interact according to these rules, and finally present the resulting distributions of animals for comparison with real-world distributions. Lack of real-world data for most oceanic animals hampers both the establishment of reasonable behavioral rules and comparison of the

computer model with real-world observations. This study has produced measurements that can be used for both. The data have been compared to an extremely simple IBM, one that assumes an isotropic Gaussian distribution of velocities. Analysis is still underway, but the results suggest that this simple model may be sufficient to describe euphausiid swimming behavior in many situations.

Related Projects

The data used in this project were originally collected by Genin and Jaffe under a grant from the U.S - Israel Binational Science Foundation. The research done under that grant has benefited from the automated tracking methods developed here. Two other projects have also benefited from the methods developed here: an ONR project by Jaffe and Franks entitled "Acoustic-Optic Integration and Visualization of 3-D Oceanic Measurement", and an NSF project by Ohman and Jaffe entitled "Combined Acoustic and Optical Imaging of Crustacean Macrozooplankton".

Publications and Presentations

A manuscript entitled "Euphausiid night-time swimming behavior: Three-dimensional *in situ* measurements compared to an individual-based model" by A. Genin, D. E. McGehee, and J. S. Jaffe is being prepared for submission to *Limnology and Oceanography* early in 1999.

Various stages of the research have been presented at three meetings, including the 1996 Joint Meeting of the Acoustical Societies of American and Japan in Honolulu (McGehee et al, 1996), the 1998 Ocean Sciences Meeting in San Diego (Genin et al, 1998), and the 1998 Joint Meeting of the International Congress on Acoustics and the Acoustical Society of America in Seattle (McGehee et al, 1998b).

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